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Optimal integration of solar energy in a district heating network

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ABSTRACT

The implementation of European Directive 2012/27 calls for the presence of a renewable share inside efficient district heating and cooling. Solar thermal energy can be a viable contribution to this aim but particular attention must be put into its integration inside the district heating systems. In fact, the variable and non-controllable nature of renewable heating must be handled by fulfilling users demand and coordinating its output with other controllable sources. Thermal energy storage is often necessary for exploiting the renewable sources at their best. An optimisation procedure has been developed to find the dispatching strategy for the different power sources present in the network. The optimisation procedure can be used at the planning level to find out the best sizing proportions of solar and conventional sources and for defining the optimal capacity of storage. After a brief description of the optimisation procedure and of its simulation modules, one test case is presented and results about advantages due to solar heating are discussed.

1. Introduction

The increase of the share of Renewable Energy Sources (RES) in energy consumption requires a larger exploitation of renewables not only in their electric form but also in the thermal one. It is common knowledge that District Heating and Cooling (DHC) network can play a pivotal role in the enhancement of RES exploitation in the thermal sector [1]. The strict interaction between electric and thermal form of energy has been exploited in the last decades by means of many cogeneration plants and district heating network. Cogeneration increases the utilisation of primary fuel leading thus to a greater efficiency and a lower greenhouse gas emission with respect to separate generation of electricity and heat. As this issue has now reached a mature technological form, Europe is raising the stakes promulgating Directive 2012/27 on energy efficiency [2] which calls for the presence of a renewable share inside the so called *efficient district heating and cooling*. Renewable share in the district heating can come by different inputs: burning renewable fuel, by the use of geothermal source, by using a renewable electric energy and converting it into heat through a reversible heat-pump or by inserting a solar heating contribution to the heating network. Anyway, the European Directive states: "*efficient district heating and cooling means a district heating or cooling system using at least 50 % renewable energy, 50 % waste heat, 75 % cogenerated heat or 50 % of a combination of such energy and heat*" [2]. In this view, the evaluation of the performances of new district heating plants, or the refurbishment of older ones, requires the analysis of the effective shares of different power sources in supplying the final user taking into account both renewable source availability and end-user demands during the different seasons of the year and within a time frame compatible with the renewable working cycle, i.e. one day if a solar input is considered.

The introduction of a renewable source with a cogeneration plant calls, in fact, for a redefinition of its management strategy. Usually the power production asset is made by a couple of components, generally a gas fired Combined Heat and Power (CHP) and a boiler. They are usually operated under a simple control loop that drives the working point of the plant in order to satisfy the user thermal demands (as it is often known as "thermal load following scheme") where CHP provides the base load and boiler covers the peak loads. If multiple power sources are present, their integration must cope with different characteristics, operational costs and technical limits, see for instance [3]. As a consequence, also with a limited number of components, the definition of a management strategy running the plant at its minimal cost or using the largest possible share of renewable is not an easy task. If intermittent and non controllable renewable sources are employed, their non predictability introduces new challenges in the plant management. A solution to the problem of non controllable renewable sources, like solar or wind, is represented by the use of energy storage. If storage elements are useful for smoothing out production levels of renewables, their intrinsically *integral* nature requires that the energy

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Nomenclature and units

a_1	first degree coefficients of the collector heat losses, (W/(Km^2))
a_2	second degree coefficients of the collector heat losses, (W/(Km)^2)
$B_c(t_i)$	input power of boiler, (kW)
c	operational cost function, (€)
c_f	average natural gas price supplying CHP, (€/m^3)
c_b	average natural gas price supplying boiler, (€/m^3)
c_s	price of electricity sold to the grid, (€/kWh)
D_t	thermal dissipation term, (kW)
$F'(\tau\alpha)_{en}$	effective transmittance–absorptance product with normal incidence, (p.u.)
G, G_0	global irradiance on the collector plane, (W/m^2)
G_{bn}	direct irradiance on a plane normal to the solar beam, (W/m^2)
G_{dh}	diffuse irradiance on the horizontal plane, (W/m^2)
G_{th}	total irradiance (direct and diffuse) on the horizontal plane, (W/m^2)
K_{M}	meteorological factor, (−)
$K_{\theta\text{b}}$	incidence angle modifier for direct irradiance, (−)
$K_{\theta\text{d}}$	incidence angle modifier for diffuse-type irradiance, (−)
MOT	minimum on time, (h)
MST	minimum shutdown time, (h)
N	number of time intervals within scheduling period
$P_e(t_i)$	electric power produced by CHP, (kW)
$P_t(t_i)$	thermal power produced by CHP, (kW)
$P_c(t_i)$	input power of CHP, (kW)
$P_s(t_i)$	storage input thermal power, (kW)
S	collector surface, (m^2)
$S_t(t_i)$	value of stored energy, (kWh)
T_a	ambient temperature, (K)
T_f	mean input/output temperature of the collector fluid, (K)
U_t	user demand of heat power, (kW)
β	collector tilt angle, (rad)
η	collector efficiency, (−)
η_0	collector zero-loss efficiency (optical efficiency), (−)
η_e	CHP electrical efficiency, (−)
η_t	CHP thermal efficiency, (−)
η_b	boiler efficiency, (−)
η_d	storage efficiency in one time interval, (−)
Δt	time length of each interval within scheduling period, (h)
$\delta(t_i)$	binary variable representing the on/off status of CHP
ρ	ground reflection factor (albedo), (−)
θ	incidence angle between the solar beam and the normal to the collector, (rad)

management is not only trying to minimise costs for a single time instant but over a time interval: for instance the energy produced by a solar plant during the day can be stored and used later.

In addition to the integration of RES, another critical issue that nowadays can be often found in DHC network management is the interaction among producers that can, for instance, add their heat contributions to the network. In this case, heat can be coming from different processes and thus can have its own time profile which must be matched with the overall requirement of the final users.

Starting from the previous considerations, the use of a simulation and optimisation tool is crucial for the evaluation of a DHC network both in the planning phase and in the real-time one. In the past twenty years, different approaches have been proposed for the solution of the management problem in different application areas ranging from the commitment of power stations as in Ref. [4] or to the management of CHP plants as in Ref. [5] or to the DHC system as in Ref. [6]. More recently, the optimisation concept has been applied to the management of complex energy systems with more than one energy source as in Refs. [7–10]. The optimisation of renewable energy sources has been approached as well in Refs. [11–13] where different aspects of the integration of distributed facilities and on the definition of expansion potential of the solutions are analysed.

The original point of the present paper stands in the application of one optimal energy management procedure to the evaluation of performances of district heating with a significant renewable energy contribution. When applied in the plant planning or refurbishing phase, the procedure gives a reliable share of the different power sources enabling thus the assessment of the degree of accomplishment of the criteria defined in the European Directive on energy efficiency [2].

Starting from the experience gained in the management of classical DHC systems, the present paper deals with the simulation and optimisation issues related to the insertion of RES in the system. In the next section an outline of the simulation of the solar thermal system is proposed while in the third section the main characteristics of the optimisation procedure are described. In the fourth section the description of the test case is given together with the discussion of the most important results. Finally some conclusions and perspectives are drawn.

2. Solar collector model

The solar collector model is based on the Steady State Test of the European Standard EN12975 [14,15]. According to Steady State Test, the collector efficiency and the output power P_{sh} are given by:

$$\eta = \frac{P_{\text{sh}}}{GS} = \eta_0 - \frac{a_1\left(T_f - T_a\right)}{G} - \frac{a_2\left(T_f - T_a\right)^2}{G} \quad (1)$$

$$P_{\text{sh}} = \left[\eta_0 G - a_1\left(T_f - T_a\right) - a_2\left(T_f - T_a\right)^2\right]S \quad (2)$$

The parameters η_0, a_1 and a_2 are usually reported in the collector data sheets. Appendix describes a more accurate model for flat-plane collectors which takes into account the Incidence Angle Modifier (IAM), as in the Quasi Dynamic Test of EN12975.

The global irradiance G_0 on the collector plane is the sum of three contributions corresponding to the direct radiation, to the diffuse radiation and to the ground reflected radiation:

$$G_0 = G_{\text{bn}} cos\theta + G_{\text{dh}}\frac{1+\cos\beta}{2} + \rho G_{\text{th}}\frac{1-\cos\beta}{2} \quad (3)$$

where typical ρ value is in the range 0.1 ÷ 0.3.

In clear sky conditions, the irradiance can be evaluated with the Moon–Spencer model [16]. The full expressions of the parameters G_{bn}, G_{dh} and G_{th} and of the incidence angle θ can be found in Ref. [17].

The clear sky irradiance G_0 has to be reduced to take into account the meteorological conditions (clouds, haze etc.) through an empirical factor K_M: